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Progress in 3D Tomographic Cloud Reconstruction, Part 1*:

MISR's perspective on the "hidden zone" inside opaque convective clouds

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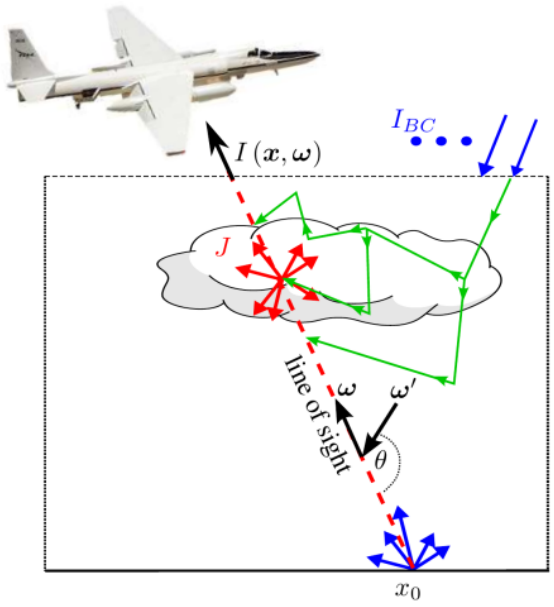
Bernhard Mayer, Ludwig-Maximilian-University, Munich

*** For Part 2 of this progress report, see poster by A.B. Davis et al.**

3D tomographic cloud reconstruction

A. Levis et al. (2015, 2017): multi-angle AirMSPI observations



$$I(x,\omega) = \int J(x',\omega)\beta(x')\, e^{-\int \beta(r)dr} dx' + I_{BC} e^{-\int \beta(x\prime)dx\prime}$$

$$J(x,\omega) = \frac{\varpi}{4\pi} \int_{s^2} p(x, \omega \cdot \omega') I(x,\omega') d\omega'$$

- Reconstruction treated as a large inverse problem
  - using “surrogate” forward model methodology
- 3D radiative transfer equation as forward model
  - using SHDOM as solver

3D tomographic cloud reconstruction

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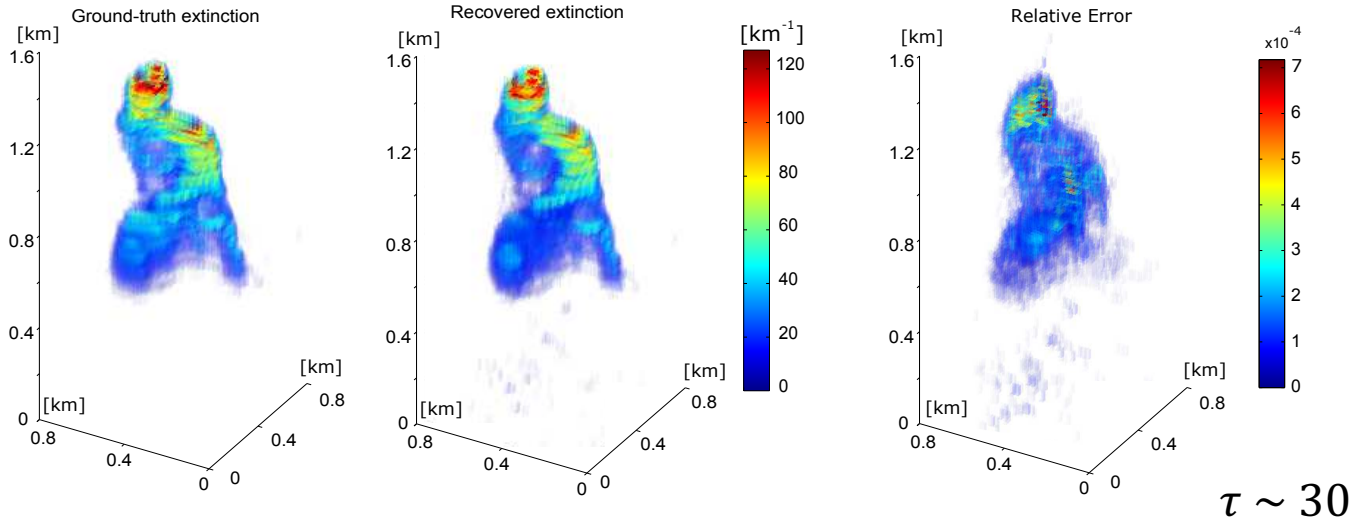


- First demonstrated on two model clouds generated with JPL LES, then applied to AirMSPI observations of a real cloud
  - 20 m spatial resolution

3D tomographic cloud reconstruction

Going from airborne to space-based observations

AirMSPI on ER2

- Adapt tomographic cloud reconstruction method from airborne (~20 m pixels) to satellite observations (~275 m pixels).

- Challenges:
  - Unresolved spatial variability of cloud microphysics
  - Optically thick cloud volumes inside MISR pixels

3D tomographic cloud reconstruction

From air-borne to space-borne observations

AirMSPI on ER2

- Adapt tomographic cloud reconstruction method from airborne (~20 m pixels) to satellite observations (~275 m pixels).

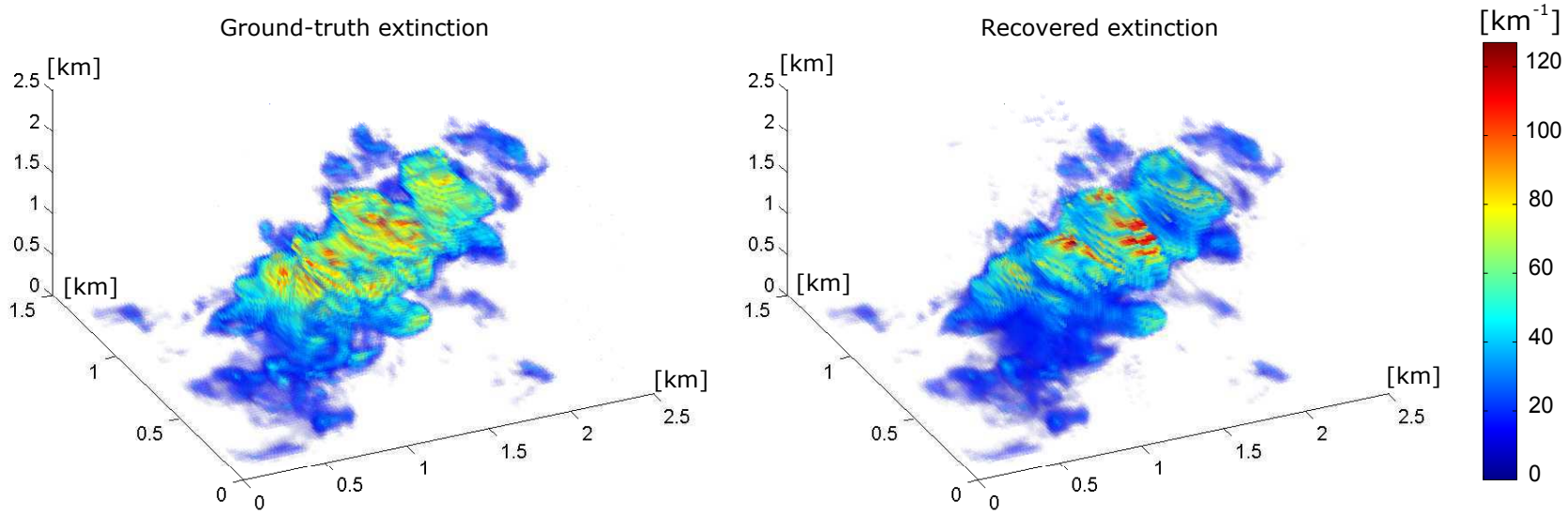
→ Develop 3D RT forward model with *efficient* transport *deep* inside optically thick clouds.

  - Possible candidate: photon diffusion theory?

→ Inform inverse problem solver about how to not waste time on spatial details *deep* inside such clouds.

The “hidden zone”?

A. Levis et al. (2015, 2017): multi-angle AirMSPI observations



$\tau \sim 50$

The “hidden zone”:

Photons scattered in and out of this region in the cloud **do not contribute significant information** about microphysical details to the observed radiances

Is the "hidden zone" related to the "diffusion domain" discussed in the literature?

- Twomey et al. 1967: $\tau \gtrsim 10$, Deirmendjian 1969: $\tau \gtrsim 16$, van de Hulst 1980: $\tau \gtrsim 14$

- Bohren et al. 1994:

At What Optical Thickness Does a Cloud Completely Obscure the Sun?

CRAIG F. BOHREN, JEFFREY R. LINSKENS, AND MICHAEL E. CHURMA

Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

6 October 1993 and 5 August 1994

- King et al. 1989:

Determination of the Spectral Absorption of Solar Radiation by Marine Stratocumulus Clouds from Airborne Measurements within Clouds

MICHAEL D. KING

Laboratory for Atmospheres, Goddard Space Flight Center, NASA, Greenbelt, Maryland

LAWRENCE F. RADKE AND PETER V. HOBBS

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

(Manuscript received 8 June 1989, in final form 9 November 1989)

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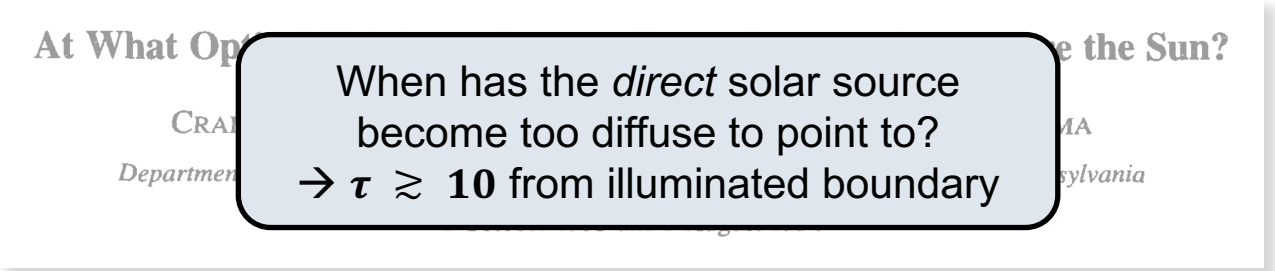
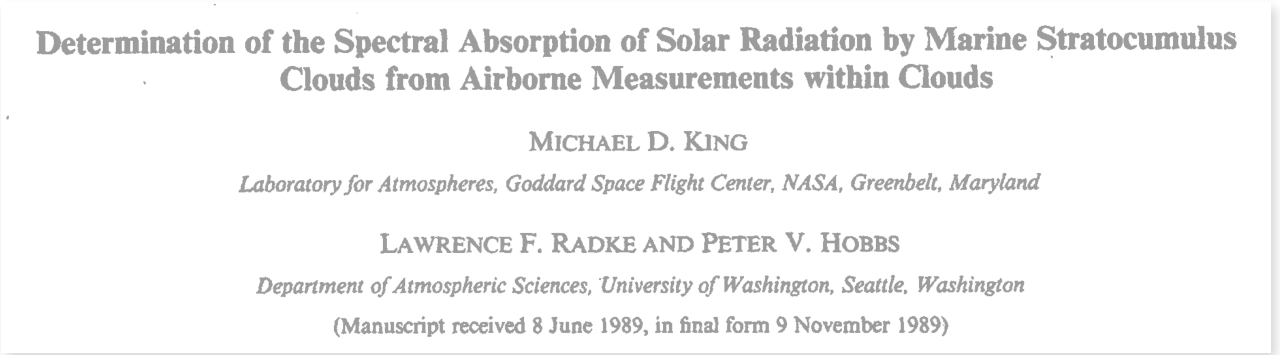

At What Opt… …e the Sun?

CRA… …MA

Departmen… …sylvania

When has the *direct* solar source become too diffuse to point to?
→ $\tau \gtrsim 10$ from illuminated boundary

- King et al. 1989: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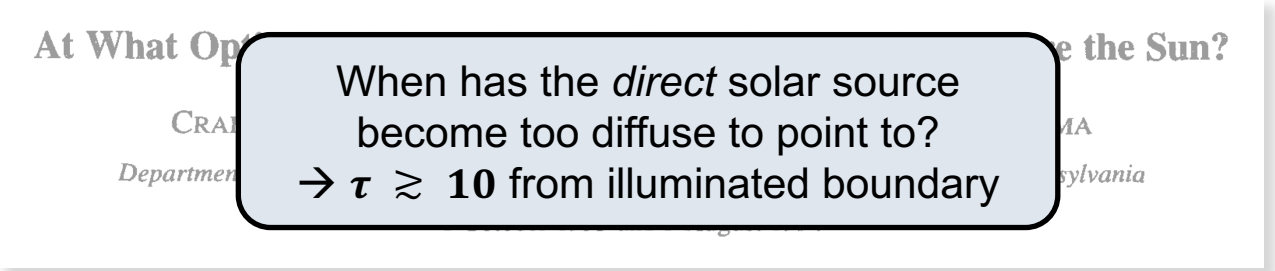

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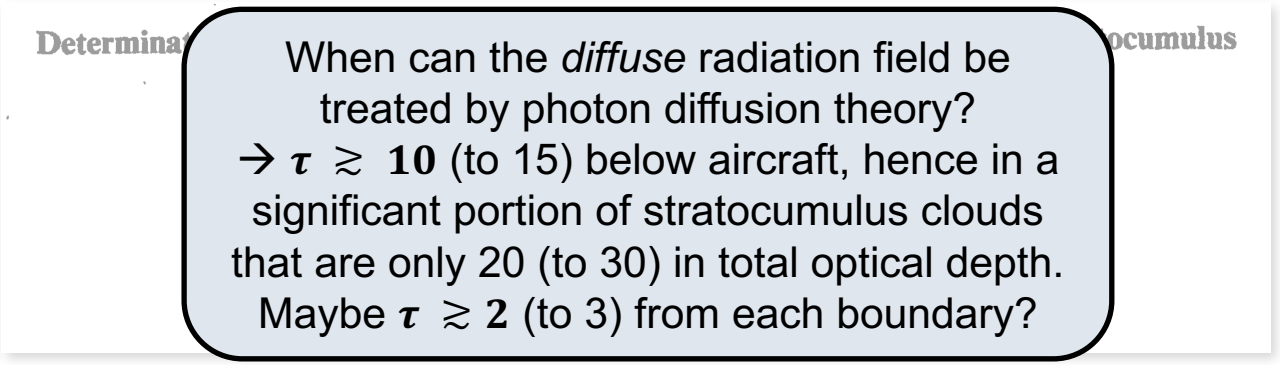


When can the *diffuse* radiation field be treated by photon diffusion theory?
→ $\tau \gtrsim 10$ (to 15) below aircraft, hence in a significant portion of stratocumulus clouds that are only 20 (to 30) in total optical depth.
Maybe $\tau \gtrsim 2$ (to 3) from each boundary?

Two related questions

1. How can we define the “hidden zone” inside clouds and where is it?

2. To what extent do photons scattered from this “hidden zone” deep inside the cloud contribute to MISR multi-angle observations?

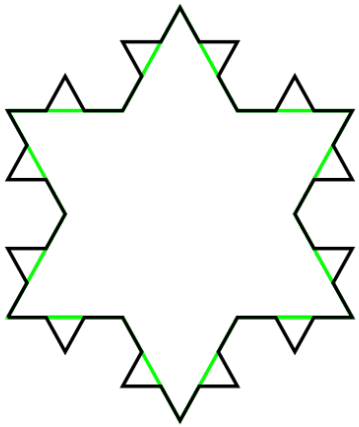
Locating the ”hidden zone”

from an airplane window

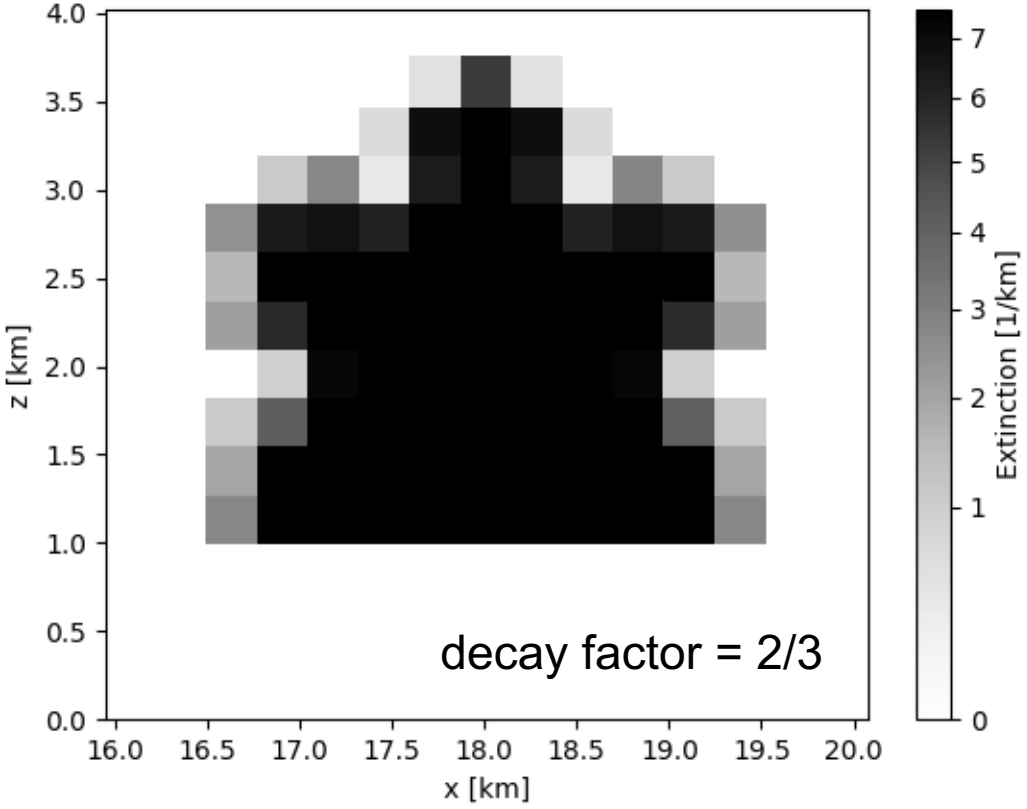
Locating the ”hidden zone”

2D Koch cloud

Koch curve



Mapped to rectangular grid



Locating the ”hidden zone”

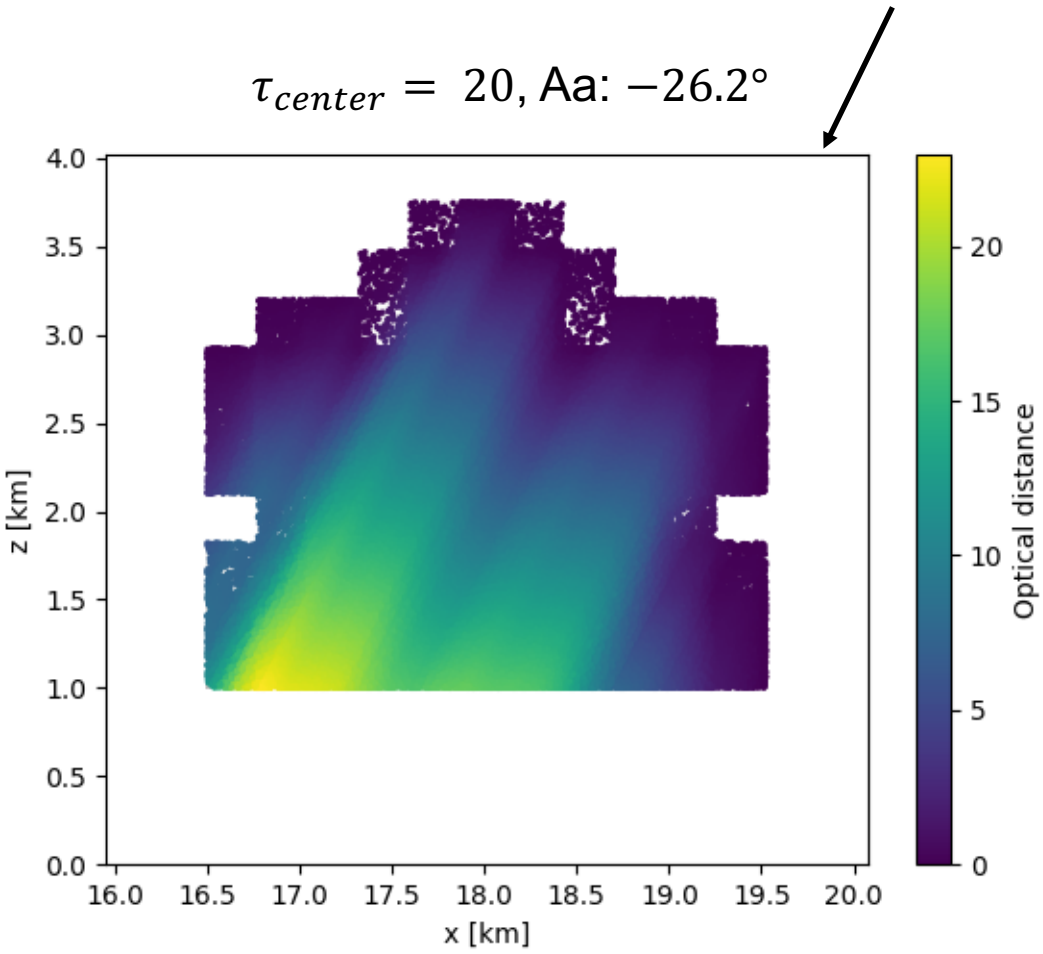
2D Koch cloud

libRadtran

Used Monte Carlo solver MYSTIC (without scattering) for photon tracing

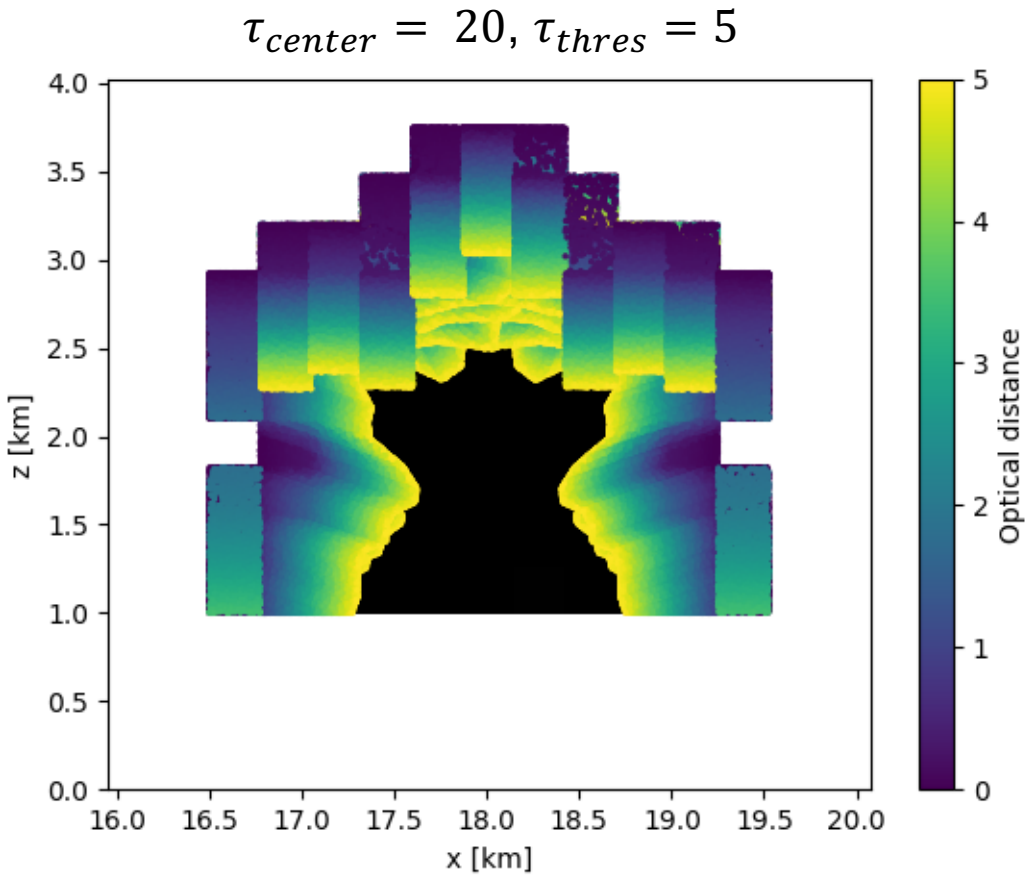
$r_{eff} = 10\ \mu m$

@ 672 nm



Locating the ”hidden zone”

2D Koch cloud, all 9 MISR cameras



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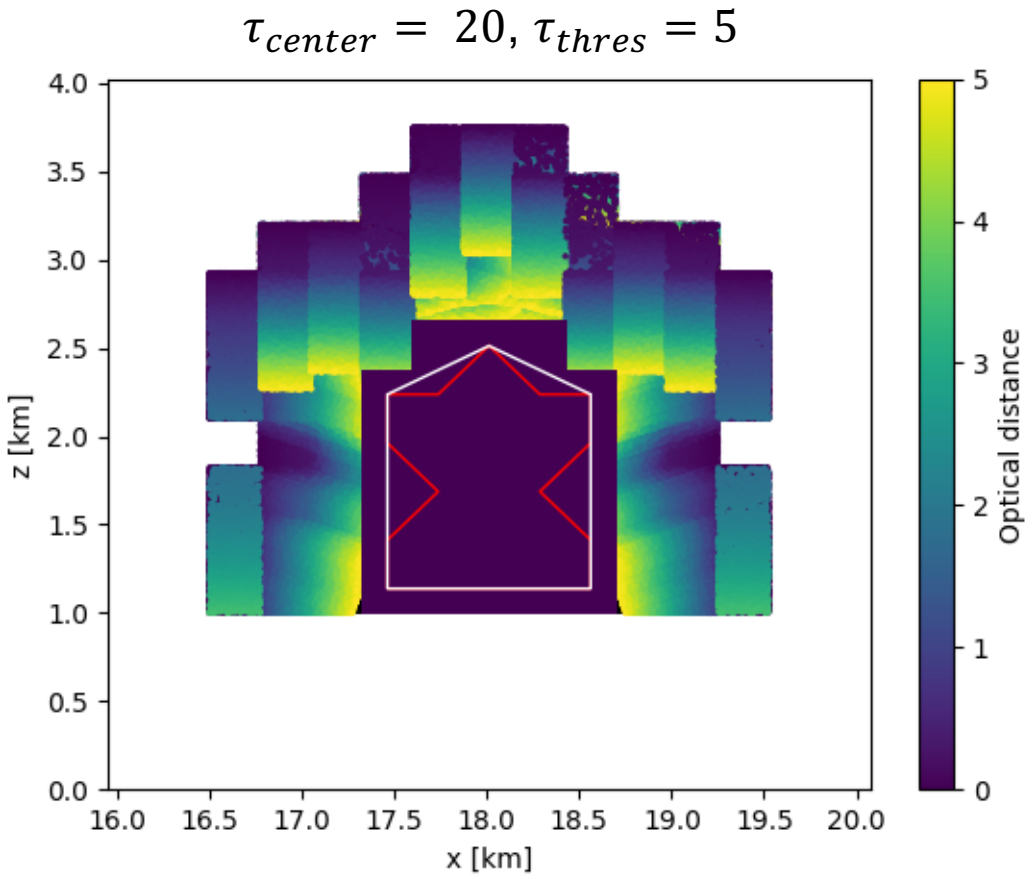
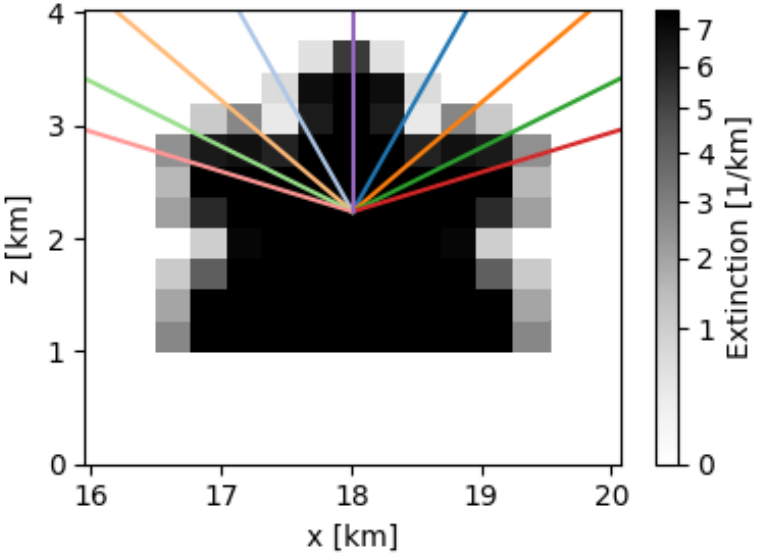


The ”hidden zone” from MISR’s perspective

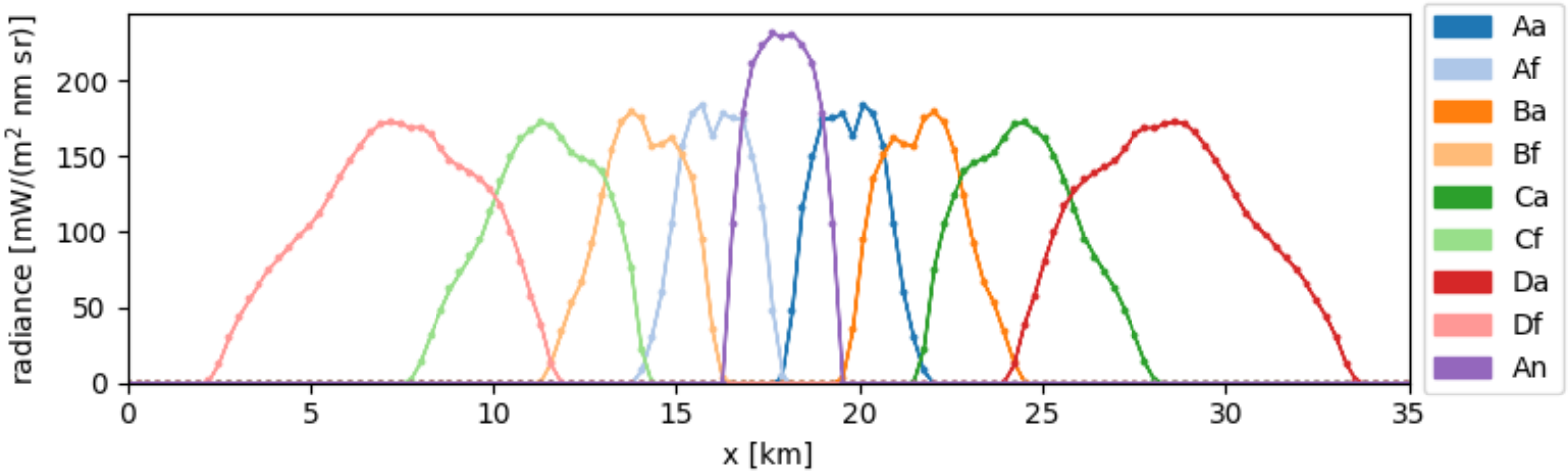
2D Koch cloud

672 nm
$SZA = 0°$
$r_{eff} = 10\ \mu m$
$\tau_{center} = 20$



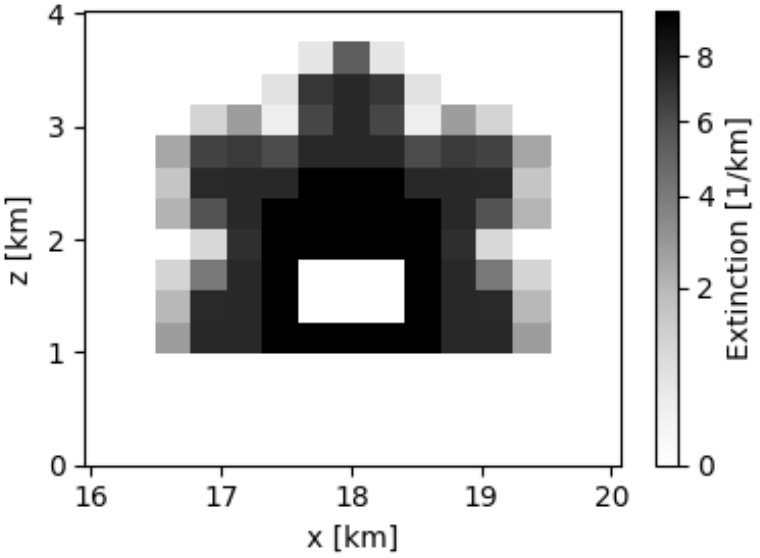
libRadtran

MISR radiances simulated with MYSTIC
(Mayer 2009,
Buras and Mayer 2011)

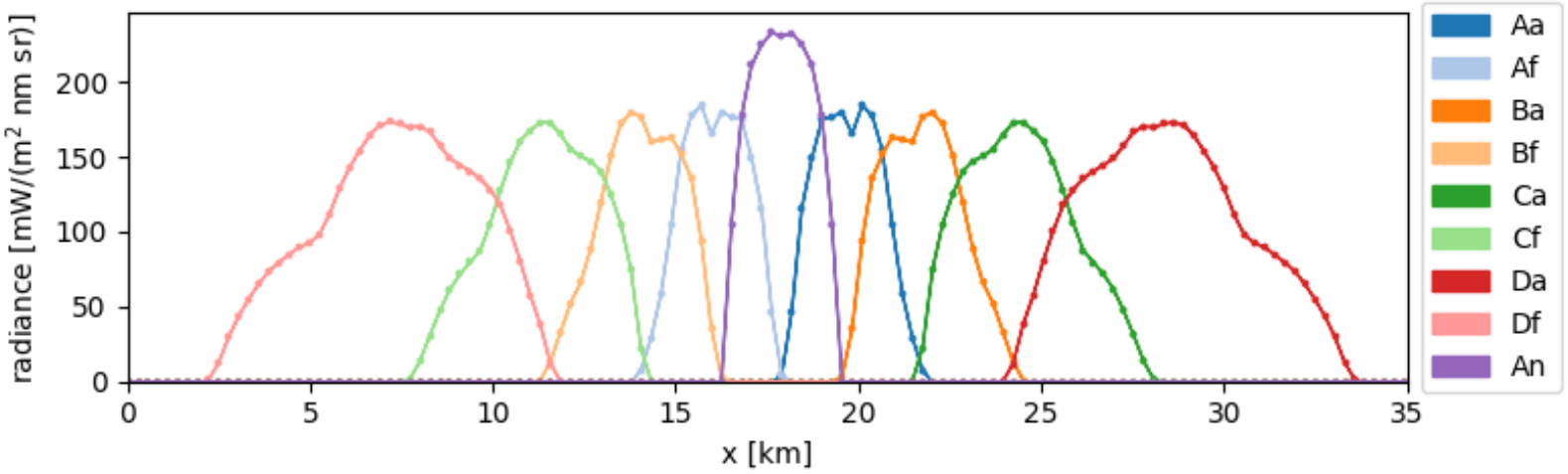


The ”hidden zone” from MISR’s perspective

2D Koch cloud



$\tau_{center} = 20$



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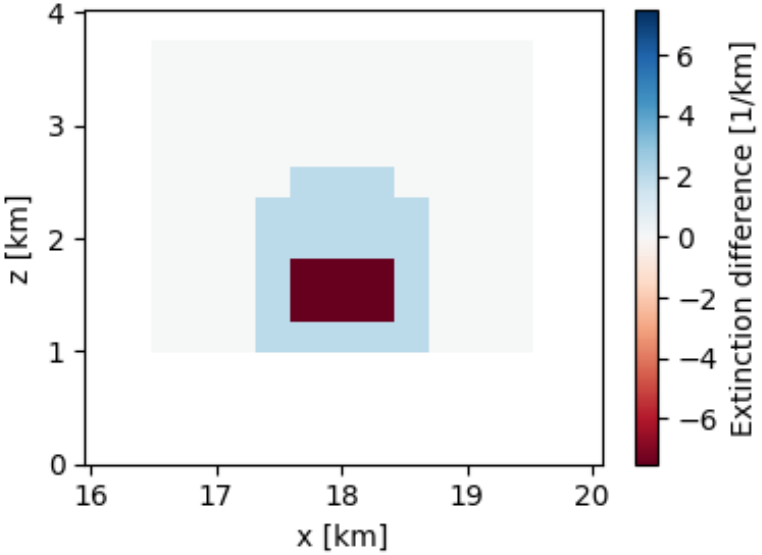
2D Koch cloud



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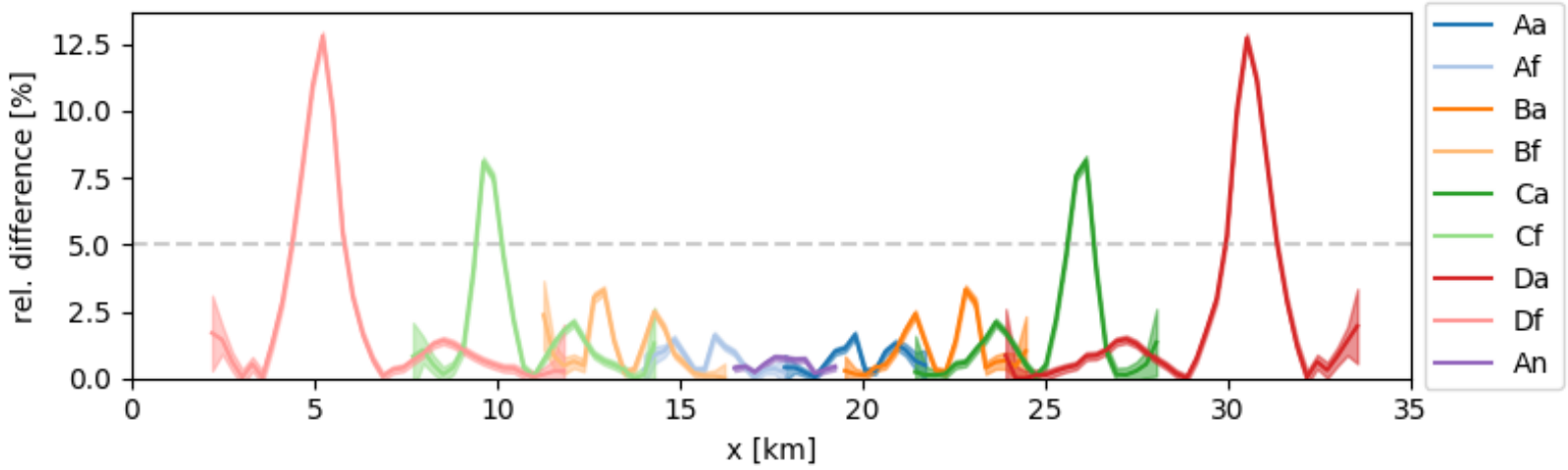
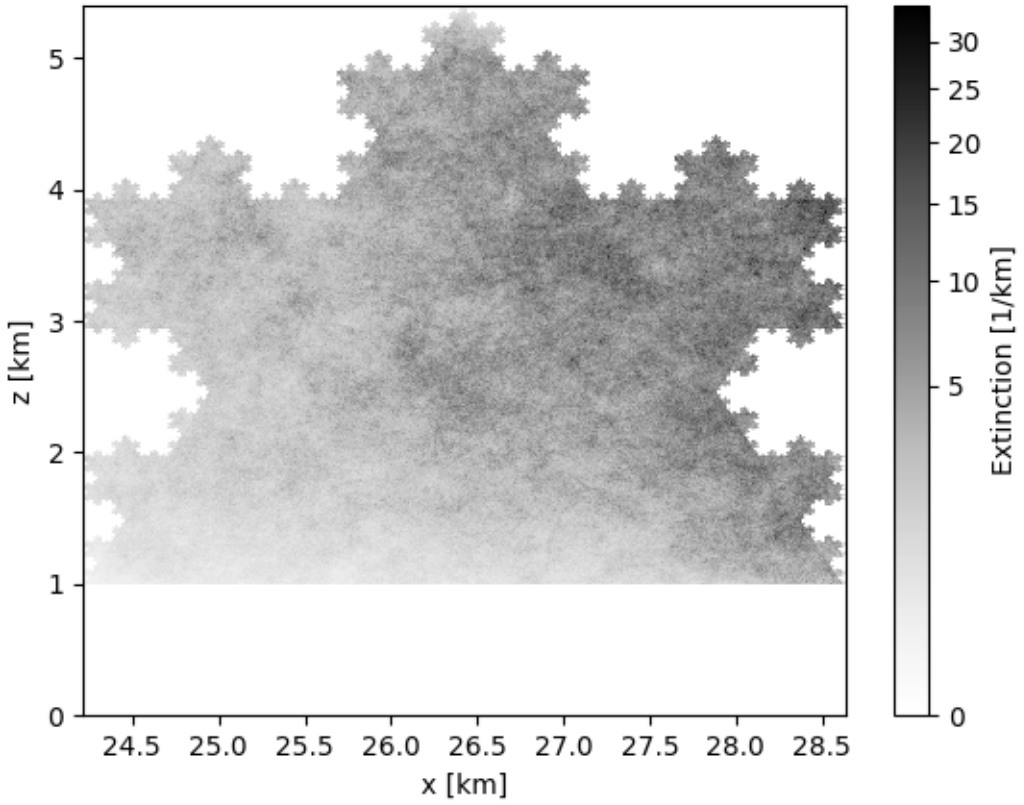


The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence

“Turbulence” is represented by a fractal Brownian surface:
Hurst exponent *H* = 1/3; 1025 x 1026 grid.



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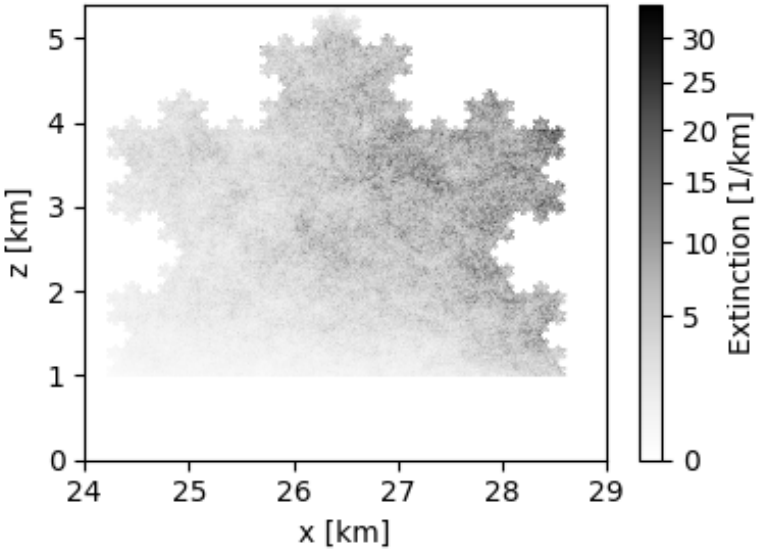
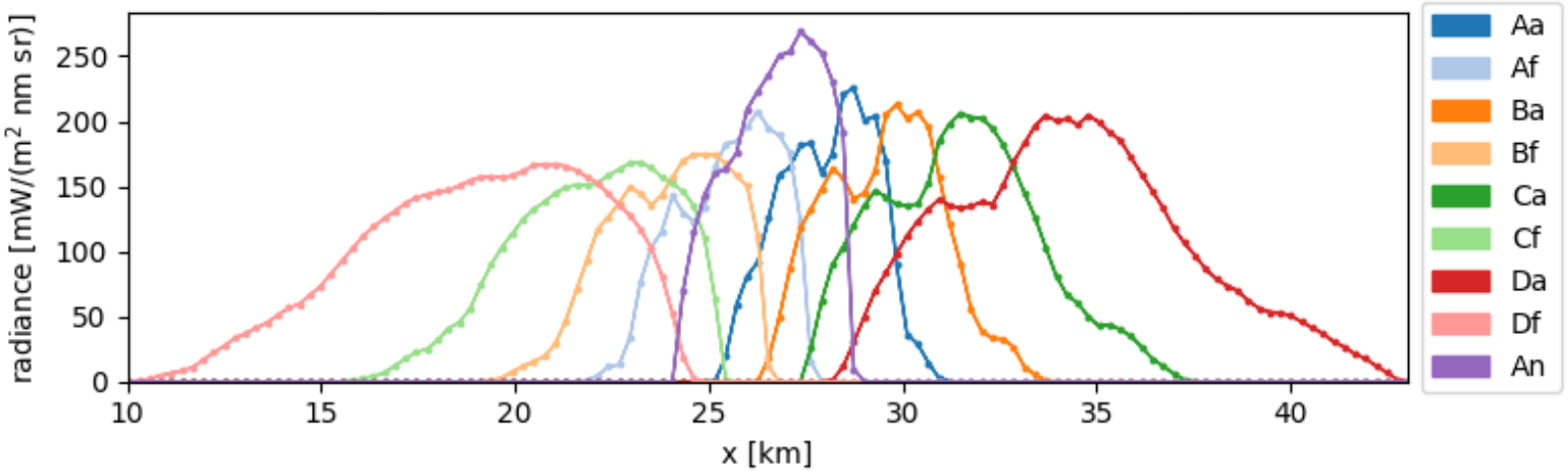
2D Koch cloud with high-resolution turbulence



Original setup

$\tau_{center} = 20$



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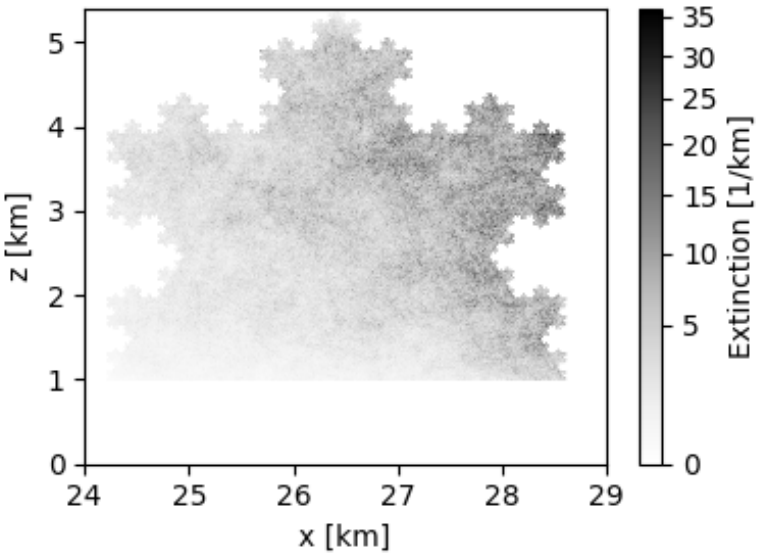
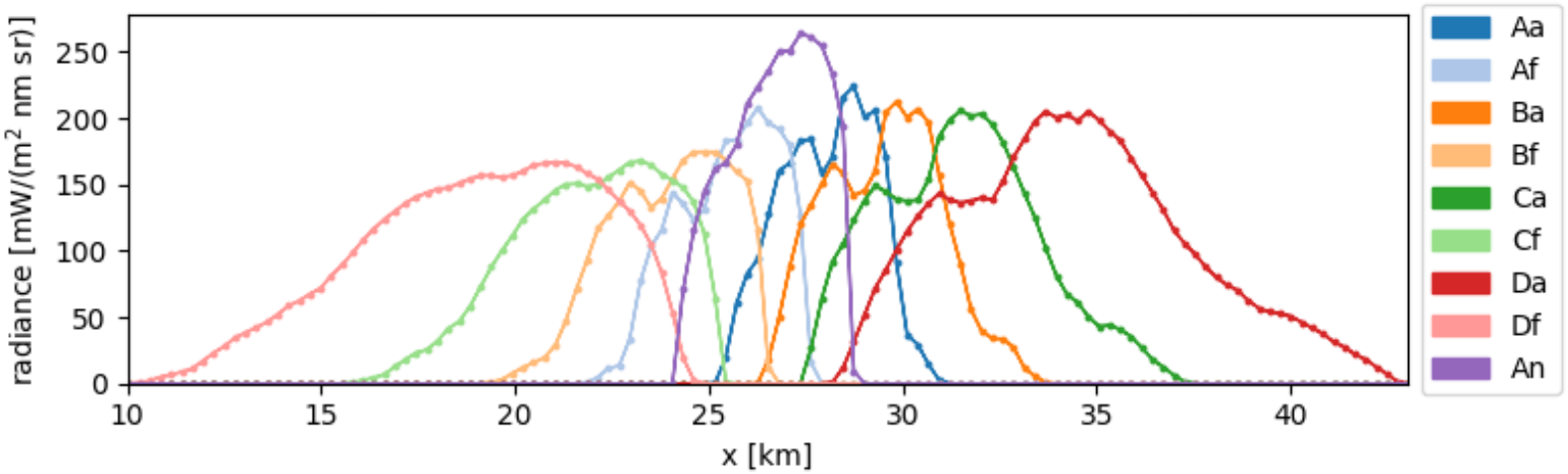
2D Koch cloud with high-resolution turbulence



Setup “center”

$\tau_{center} = 20$



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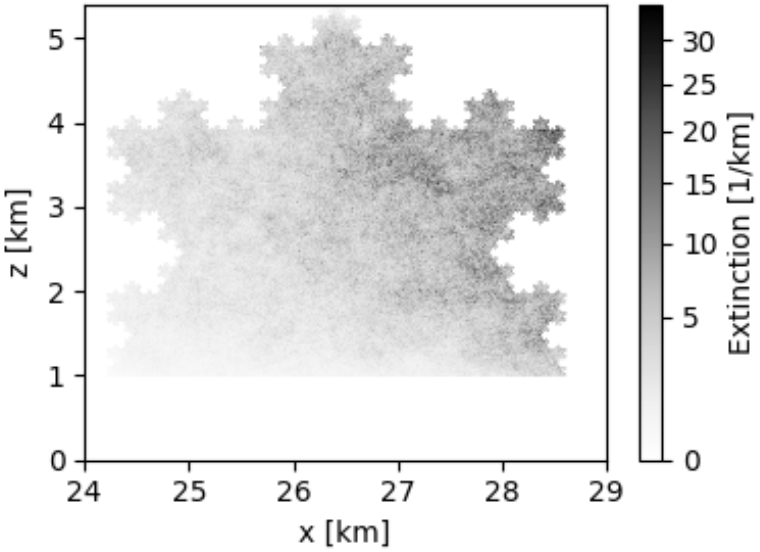
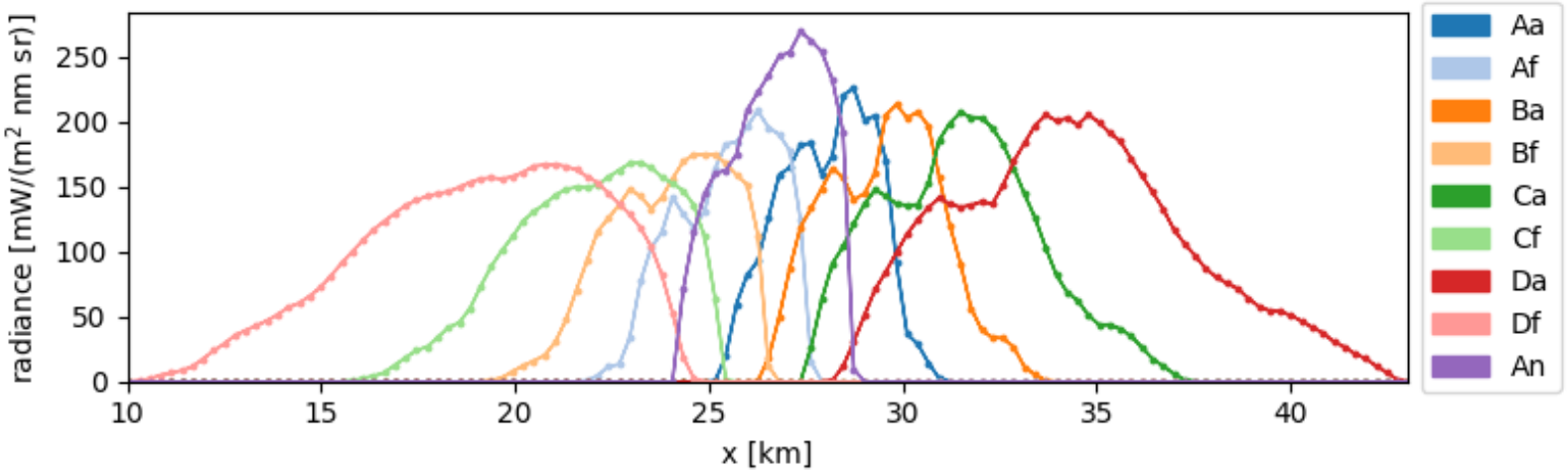
2D Koch cloud with high-resolution turbulence



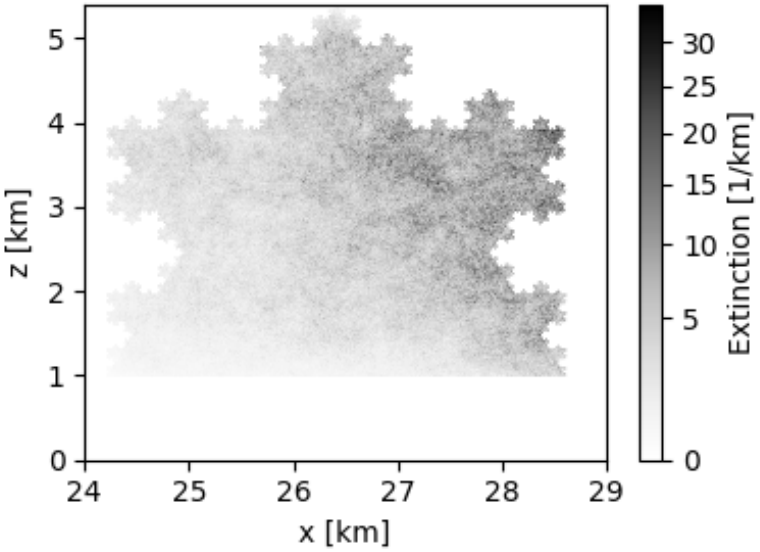
Setup
“lower” 1

$\tau_{center} = 20$



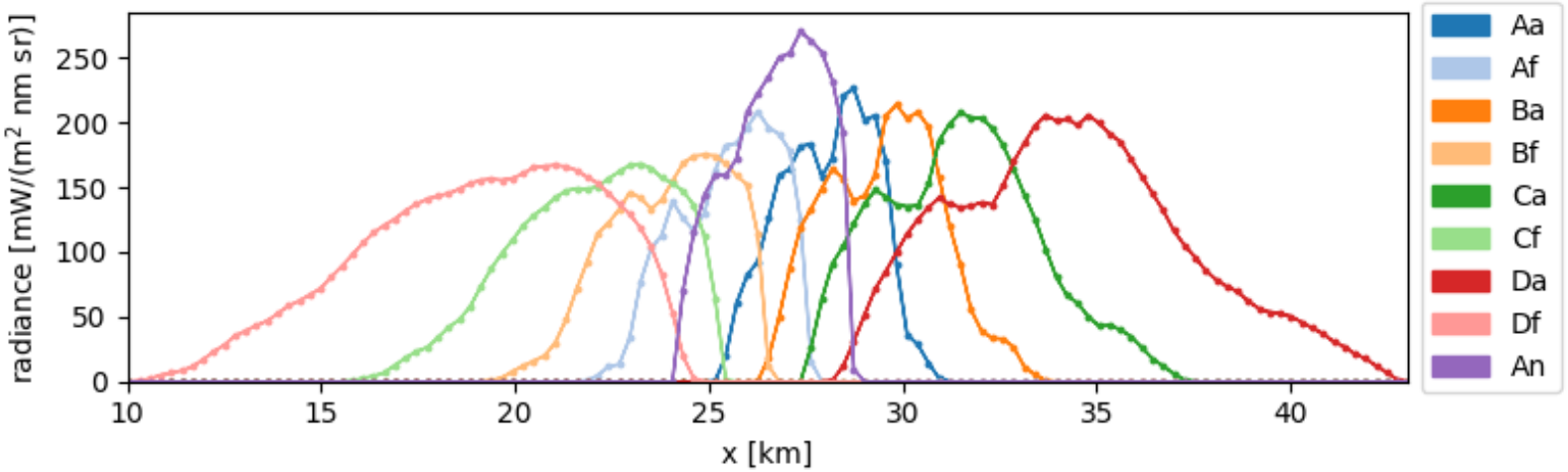
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



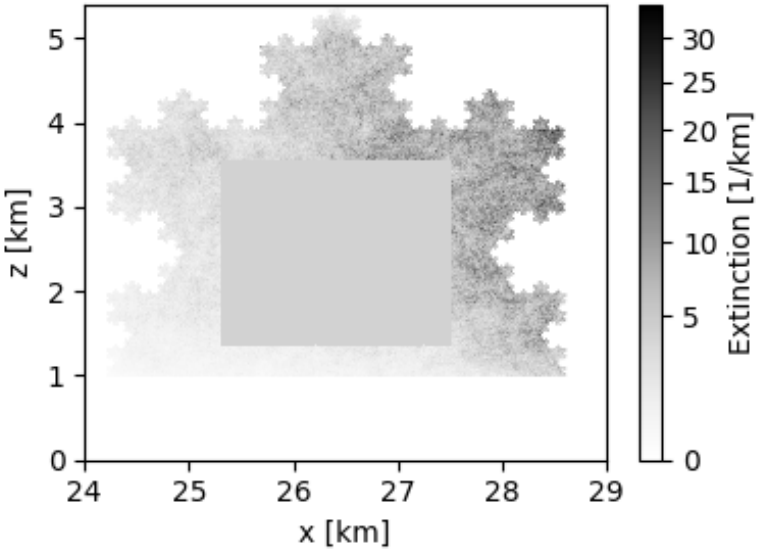
Setup
“lower” 2

$\tau_{center} = 20$



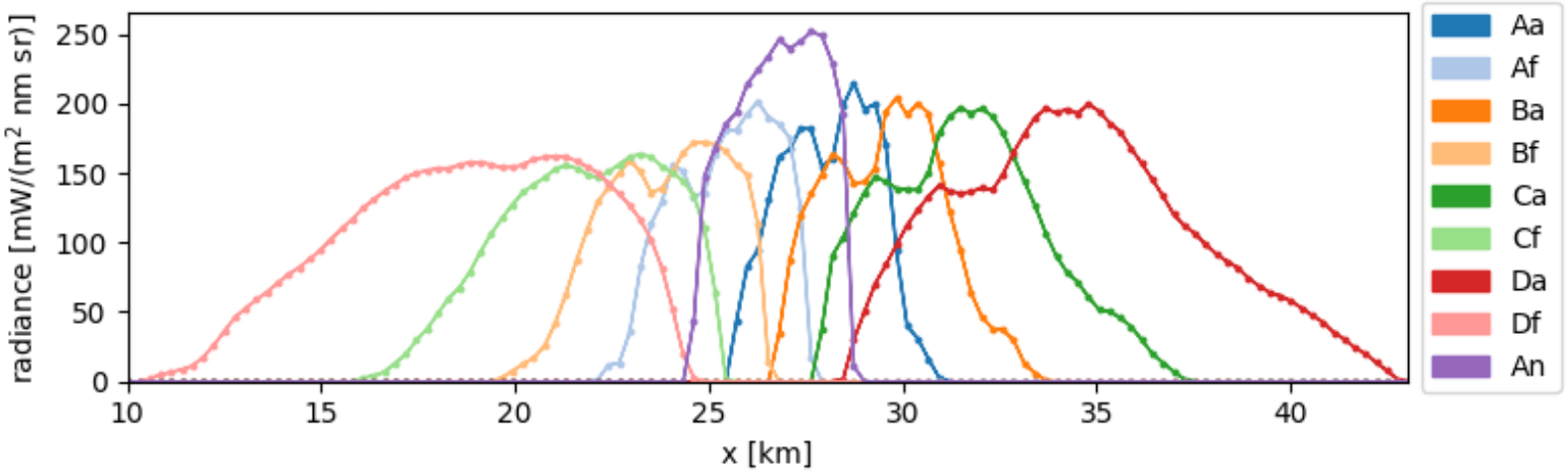
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



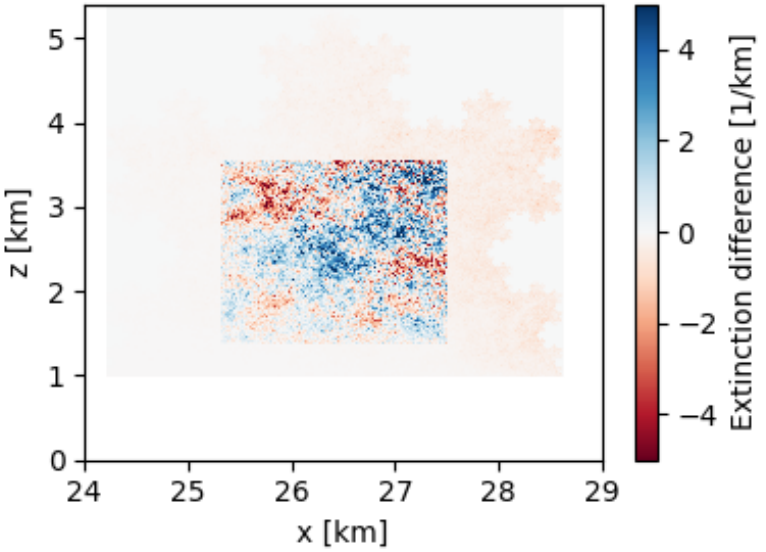
Homogeneous center

$\tau_{center} = 20$



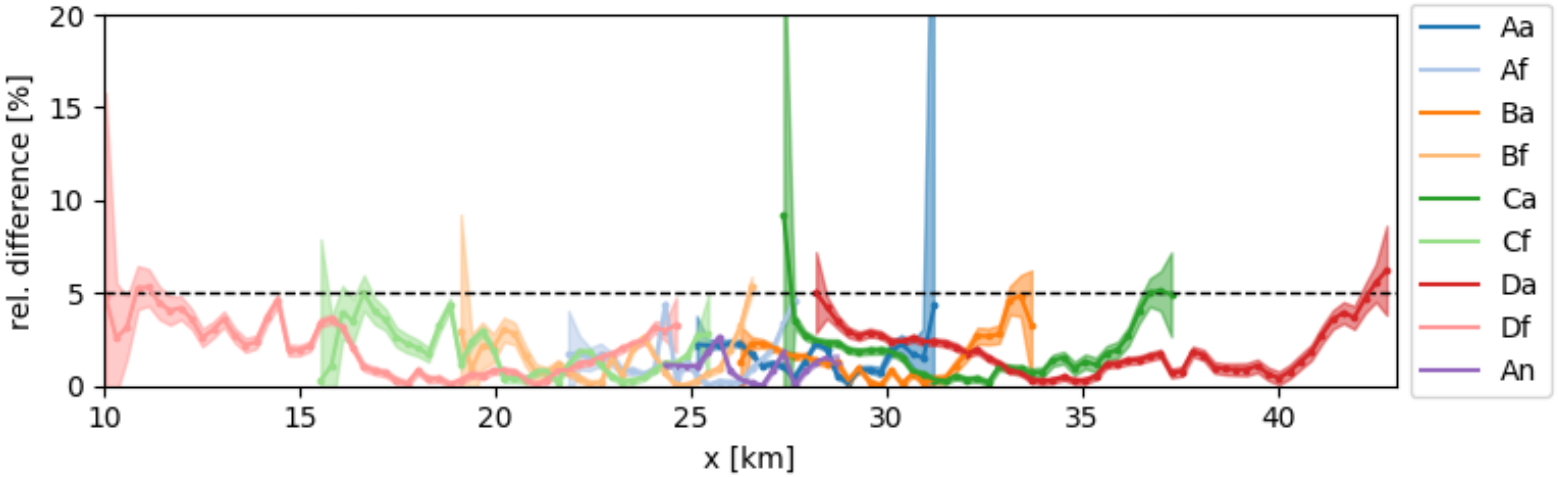
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



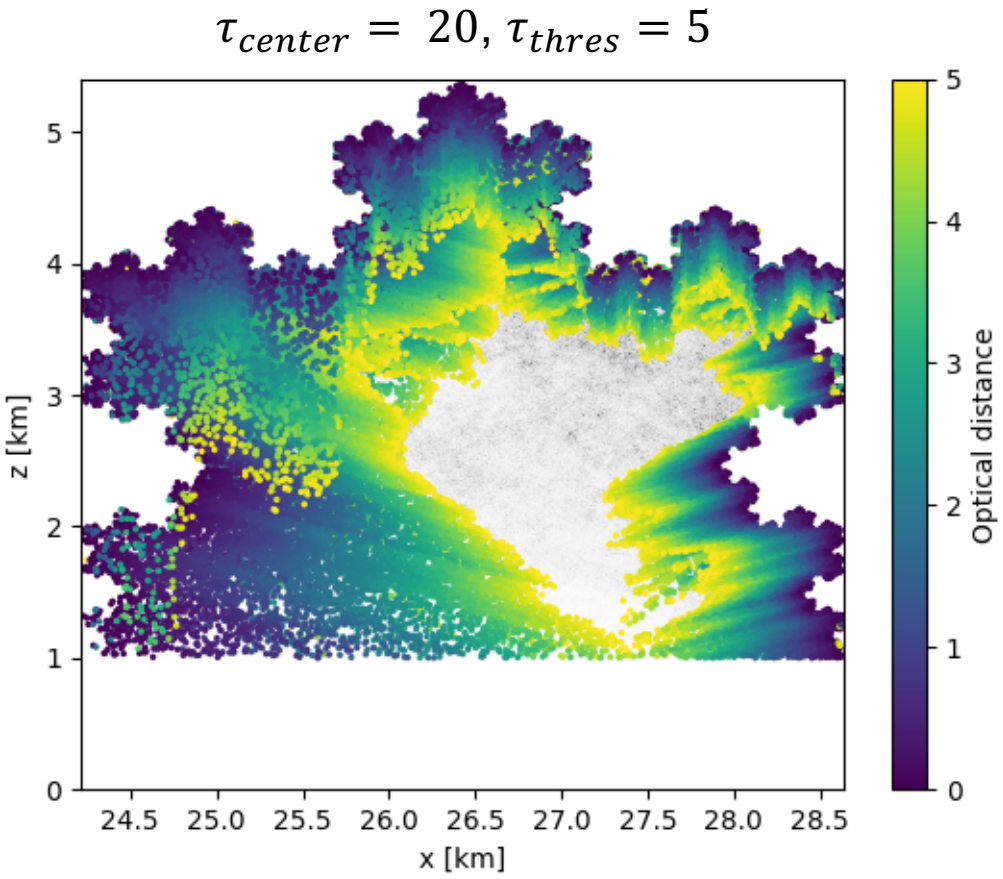
Original vs. “center”

$\tau_{center} = 20$



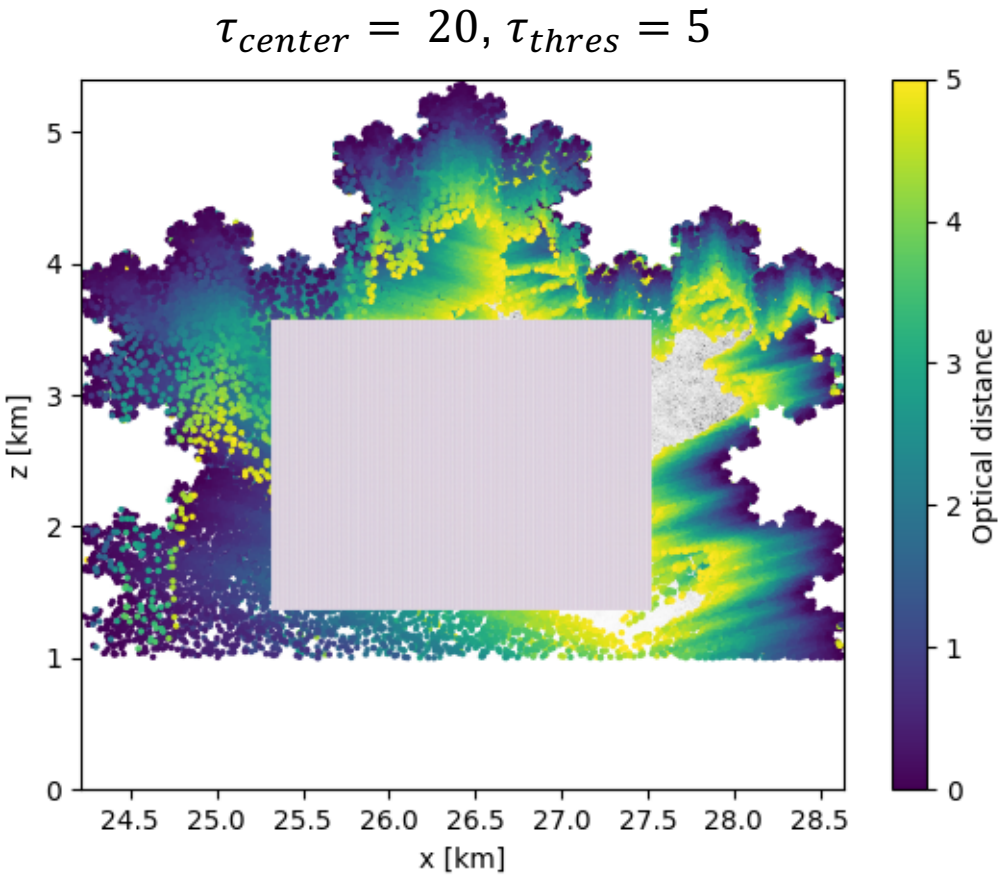
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



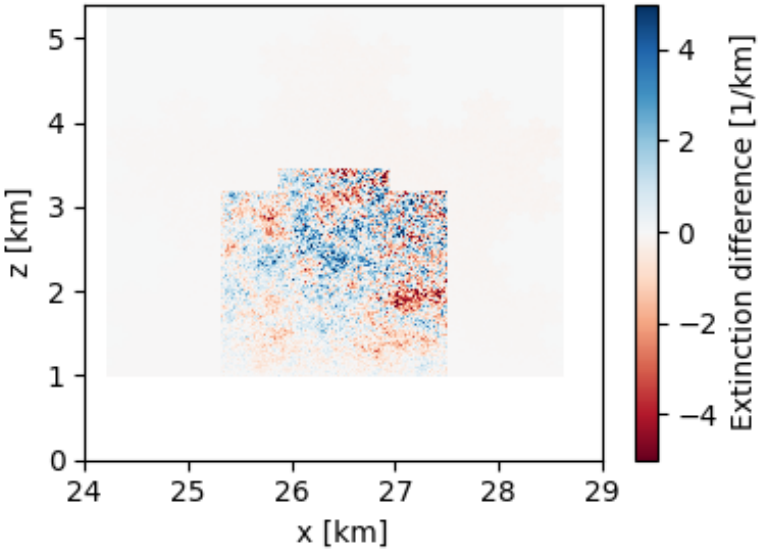
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



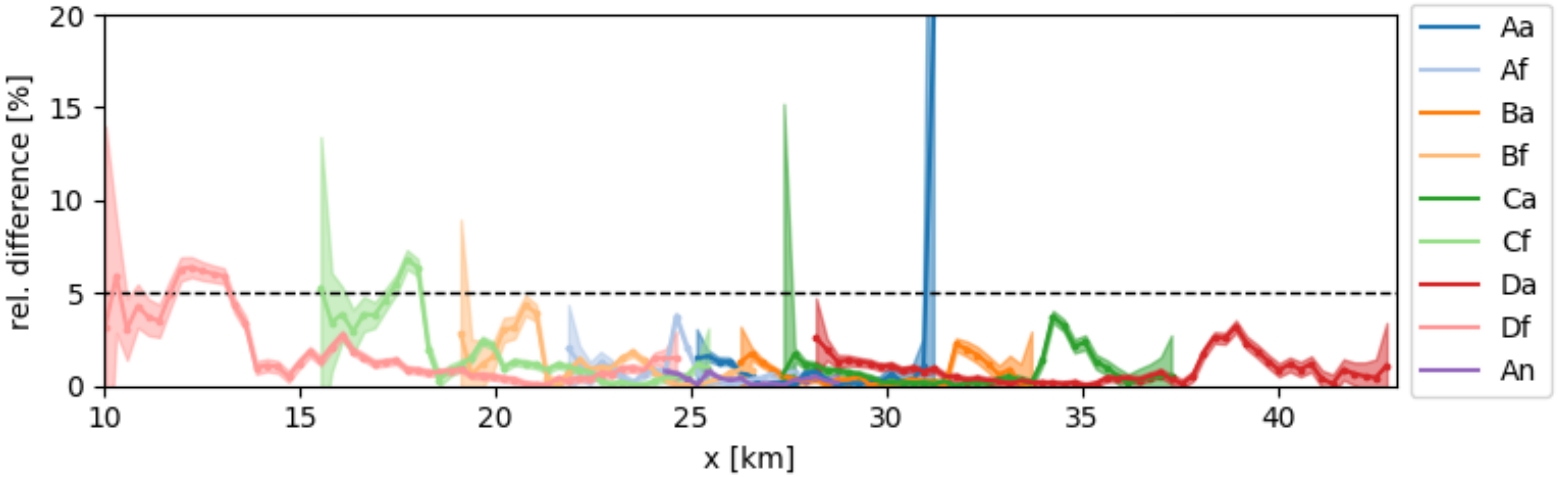
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



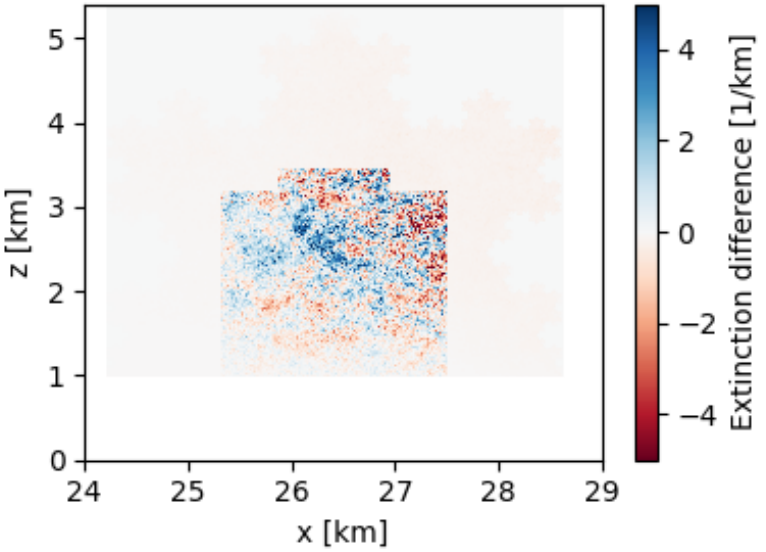
Original
vs.
“lower” 1

$\tau_{center} = 20$



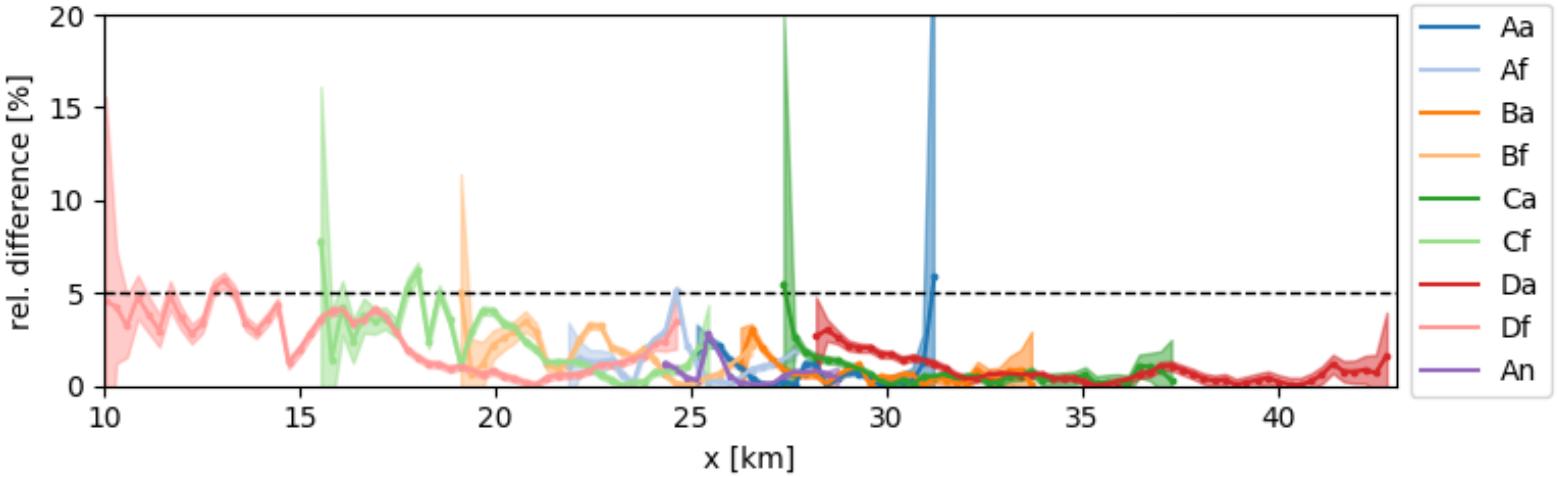
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



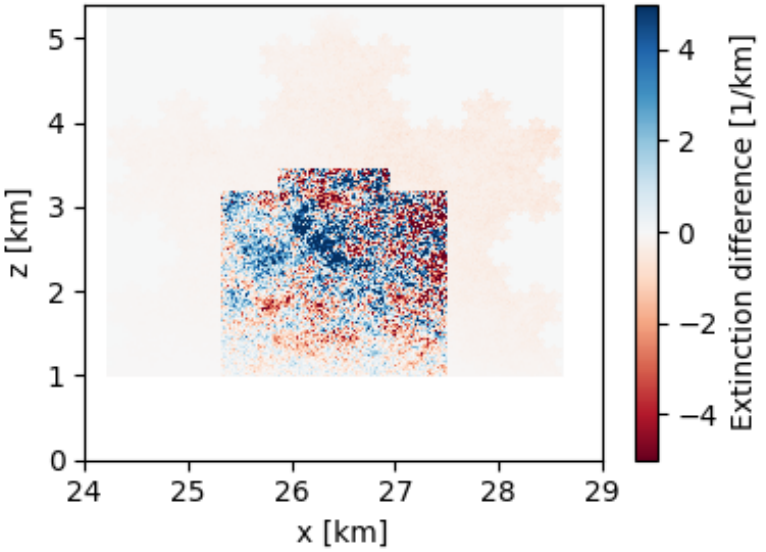
Original
vs.
“lower” 2

$\tau_{center} = 20$



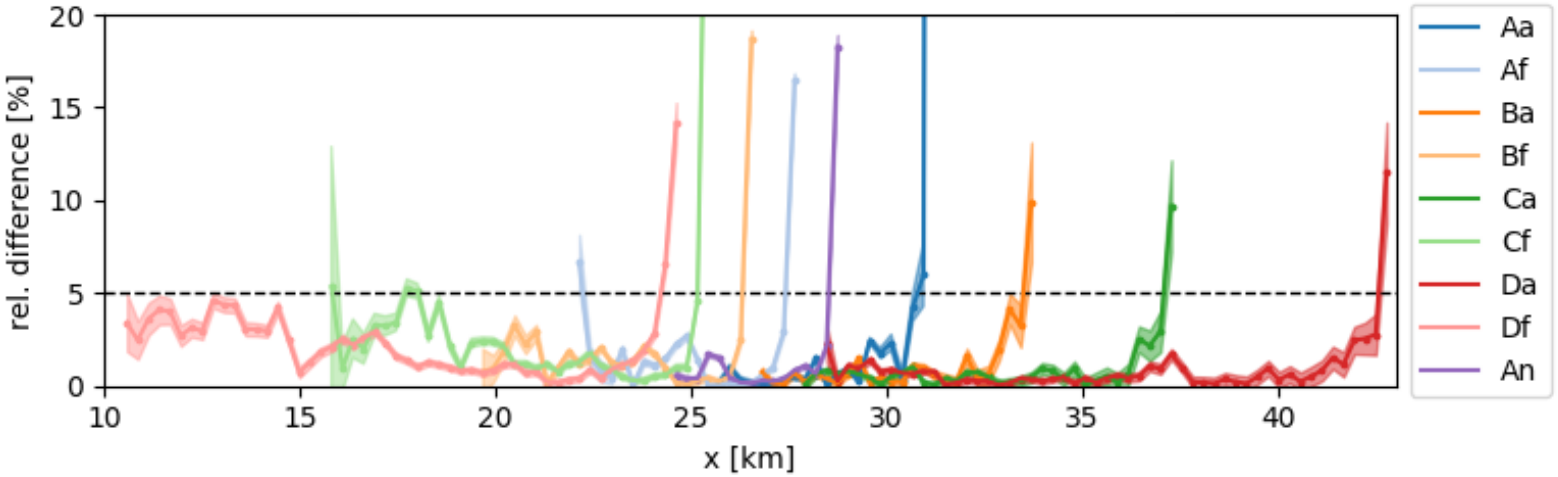
The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



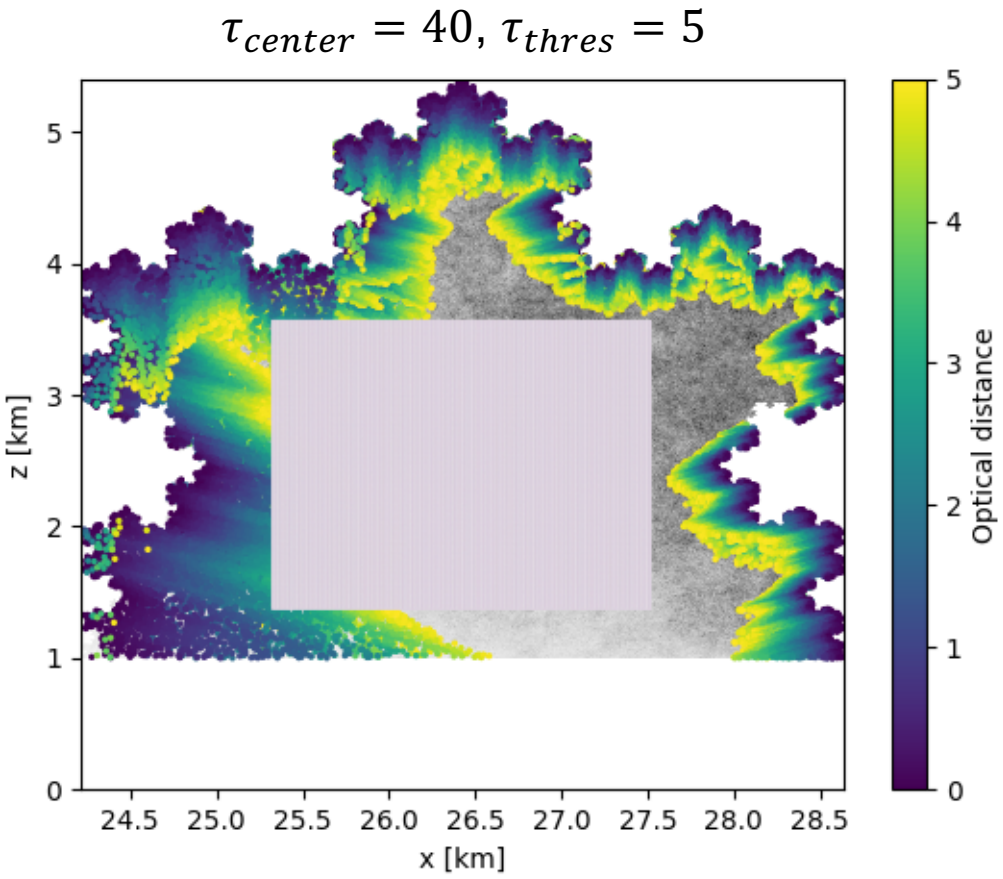
Original
vs.
“lower” 2

$\tau_{center} = 40$



The ”hidden zone” from MISR’s perspective

2D Koch cloud with high-resolution turbulence



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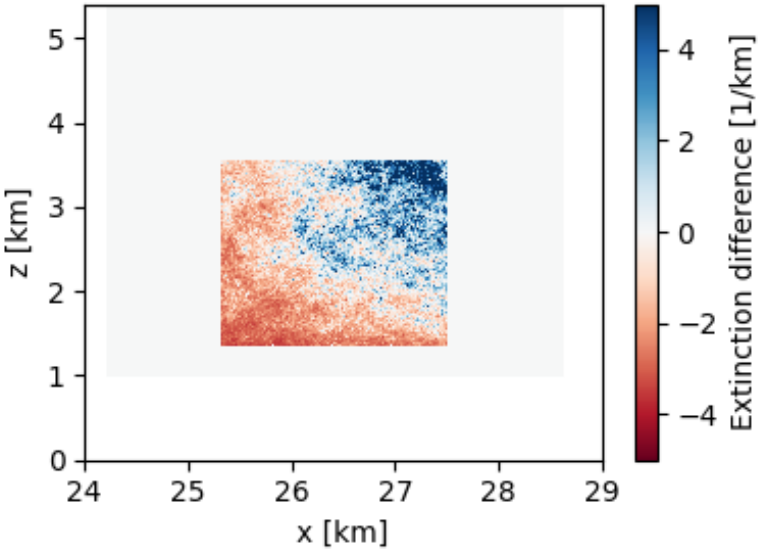
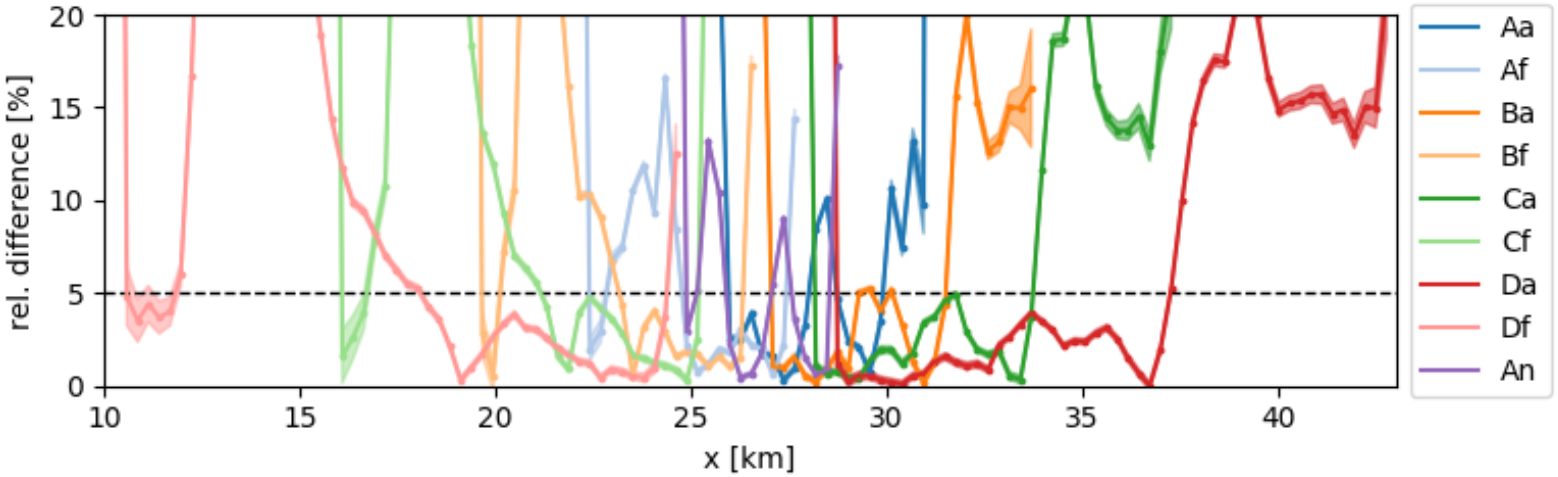
2D Koch cloud with high-resolution turbulence



Original vs. Homogeneous center

$\tau_{center} = 20$



Conclusions

- The Radiative transfer simulations showed that photons scattered from optical distances $\boldsymbol{\tau \gtrsim 5(3)}$ inside the cloud do not significantly contribute to MISR's multi-angle observations → "hidden zone".

- Changes in the distribution of the liquid water content (LWC) inside the "hidden zone" resulted in variations of the MISR radiances of <5%, as long as mean *and variance and correlations* of the LWC were preserved.

Outlook

- Investigate efficient methods to perform radiative transfer inside “hidden zone” to enable *practical* tomographic cloud reconstruction from MISR observations.
- Perform sensitivity studies of “hidden zone” for more realistic 3D clouds, specifically, from LES simulations.
- Develop a method to predict location of “hidden zone” in the 3D grid from MISR multi-angle observations.

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Thank you!

Questions?

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